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Comparison of soil moisture penetration depths for several bare soils at two microwave frequencies and implications for remote sensing

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Abstract. Microwave brightness temperature measurements were made over three different bare soils at frequencies of 5 GHz (λ = 6 cm) and 1.67 GHz (λ = 18 cm) to compare differences in penetration depth according to texture, soil moisture, and wavelength. The soil plots were wetted, and circularly polarized microwave measurements were made during the dry-down cycle. Soil profile temperature and profile moisture content were monitored continuously for the duration of the experiment. Laboratory analyses of soil physical properties such as texture and bulk density were conducted to aid theoretical calculations of the soil dielectric constants. Laboratory measurements of the soil dielectric constants were also made. Two commonly used soil dielectric models were compared. Theoretical values of soil dielectric constant were calculated with the Dobson model and the Wang-Schmugge model, and both compared reasonably well with laboratory measurements and also to values reported in the literature. Calculated soil emissivities derived from the field measurements also compared well with emissivities calculated from both the modeled dielectrics and those measured in the laboratory. Emissivities were compared with the average soil moisture for surface profiles of varying thickness. It was found that the observed effective penetration depth appeared to exceed the theoretically defined values.

1. Introduction

Accurate, large-scale estimates of both land surface evaporation and soil moisture content are difficult to make by conventional measuring techniques. Water and energy balance models are able to quantify these parameters accurately on a local scale, but because they rely on measured surface parameters, they, too, are less accurate at the regional level, especially at shorter timescales. One reason is the high spatial uncertainty of many land surface parameters such as soil moisture, surface temperature, and vegetation cover. While point sampling is for the most part reliable, areal averaging of these measurements, especially at scales of 10^2–10^3 km^2, may introduce significant errors. Soil moisture, for example, is often found to exhibit extremely large variations at spatial scales of only a few meters [*Hills and Reynolds*, 1969; *Nielsen et al.*, 1973; *Bell et al.*, 1980]. Since land surface evaporation is strongly related to the surface moisture [*Shukla and Mintz*, 1982], its variability, as a consequence, may also be high. Remotely sensed land surface measurements are therefore a logical input to regional scale and larger models, since remotely sensed observations are integrated measurements over an entire pixel and many models use spatially averaged input [*Camillo and Schmugge*, 1984; *Van de Griend and Van Boxel*, 1989]. Microwave measurements from space-based platforms may possess the greatest potential for monitoring surface moisture over large areas, especially in arid and semiarid regions.

Past investigations have compared soil microwave emissivity responses to changing soil moisture using a variety of different sensors and wavelengths. Ground, aircraft, and satellite measuring platforms have all successfully demonstrated the potential of microwave sensors for monitoring changing conditions in soil moisture [*Jackson and O'Neill*, 1990; *Schmugge et al.*, 1986; *Owe et al.*, 1992; *Van de Griend and Owe*, 1994].

An experiment was conducted to compare the microwave emissivity from the soil with the average soil moisture in surface layers of various thicknesses. Differences in penetration depth according to soil texture, soil moisture, and frequency were also investigated. Microwave brightness temperature measurements were made at two frequencies over three soils with different textural characteristics. The soils were wetted, and measurements were made during the dry-down cycle. Analyses for various soil physical properties were conducted, and laboratory measurements of the soil dielectric constants were also made. Results from two frequently used soil dielectric models and the laboratory measurements were compared for the different experimental soils. The normalized brightness temperatures were compared with theoretical emissivity estimates based on the measured soil moisture and other soil physical parameters and were also compared with emissivities calculated from laboratory measurements of the soil dielectric constant. Field radiometer measurements were also compared with the average moisture content of top soil layers from 0.5 to 8 cm in thickness.

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Table 1. Physical Properties of the Experimental Soils

Soil	Texture, %			Water Content, %		Percent Organic Matter	Bulk Density, kg/m^3
	Sand	Silt	Clay	0.2 MPa	1.5 MPa		
Forest	57.4	32.1	10.5	10.1	5.4	1.47	1.48
Natural	72.2	24.3	3.5	4.9	2.5	0.50	1.56
Sand	92.7	6.7	0.6	2.1	1.2	0.04	1.38

2. Field Measurement Procedure

Measurements were made over three bare soils with different textural characteristics. The experimental site was located at the U.S. Department of Agriculture Beltsville Agricultural Research Center (BARC) in Beltsville, Maryland. The natural soil at the experimental site was a sandy loam/loamy sand, while the two other soils were transported to the site. One was a common construction sand, while the other was a locally excavated forest soil (also a sandy loam), which was screened for removal of large stones and organic debris. Henceforth the terms natural, sand, and forest will be used in reference to the experimental soils. Table 1 provides additional detail on the soil physical properties. The imported soils were rolled periodically during construction of the plots and raked smooth to achieve maximum uniformity throughout the profile. The depth of the imported soils was 70 cm. Soil plots were then wetted thoroughly and covered for 24 hours to permit the profile to drain and achieve moisture equilibrium.

Circularly polarized microwave brightness temperature measurements were made at frequencies of 1.67 GHz (λ = 18 cm) and 5.0 GHz (λ = 6 cm). Radiometer measurements were made from a height of 2.2 m above the surface and at an incidence angle of 30° to minimize interference due to self-emission and reflection. Soil temperatures were monitored continuously for each plot with both mercury thermometers and thermistors placed in vertical profiles at 0.5, 1, 2, 4, 6, and 10 cm. Soil moisture profile measurements were made on a continuous basis by electrical resistance at 0.5, 1, 2, 3, 4, 5, and 8 cm and were calibrated by frequent volumetric moisture sampling throughout the day. All soil moisture data are expressed on a volumetric basis. Moisture contents for the soil plots ranged from near zero to approximately 20%. The experiment was conducted for 16 consecutive days, although measurements were halted on several occasions due to inclement weather.

3. Microwave Theory

3.1. Soil Dielectric Constant

The basis for microwave technology in the measurement of soil moisture content follows from the dielectric properties of soil-water mixtures and their effect on the natural microwave emission from the soil [*Schmugge*, 1985]. The dielectric constant is a complex number, containing a real (k') and an imaginary (k'') part. The real part determines the propagation characteristics of the energy as it passes upward through the soil, while the imaginary part determines the energy losses [*Schmugge*, 1985]. The dielectric constant is a difficult quantity to measure in the field. Moreover, reproducing precise field conditions in laboratory soil samples makes laboratory analysis of the dielectric constant also not entirely straightforward. Consequently, the validation of theoretical calculations is often somewhat difficult.

In a nonhomogeneous medium such as soil the complex dielectric constant is a combination of the individual dielectric constants of its components (i.e., air, water, rock, etc.). In a soil medium the dielectric constant is determined largely by the moisture content, temperature, salinity, textural composition, and frequency. At low frequencies ($\leq$5 GHz) the real part of the dielectric constant for water is large (70–80), while for a dry soil the value is low ($\cong$3). This large difference results in the measurable range in emissivity, in response to changing soil moisture conditions. *Schmugge* [1985] presents an excellent review of basic microwave theory.

The relationship between the soil dielectric constant and the moisture content is almost linear, except at low moisture contents. This nonlinearity at low moisture contents is due to the strong bonds which develop between the surfaces of the soil particles and the thin films of water which surround them. These bonds are so strong at low moisture levels that the free rotation of the water molecules is impeded. This water is often referred to as bound water. Therefore, in a relatively dry soil, the water is tightly bound and contributes little to the dielectric constant of the soil-water mixture. As more water is added, the molecules are farther from the particle surface and are able to rotate more freely. This is referred to as the free water phase. The subsequent influence of the free water on the soil dielectric constant therefore also increases. Smaller particles such as irregular fine sands, silts, and clays have a higher surface-area-to-volume ratio and therefore are able to hold more water molecules at higher potentials. The unique structure of clays provides an additional source of high-energy bonds and increases the soil's affinity for water. Two soils with different textural composition may exhibit markedly different relationships between moisture content and their respective soil dielectric constants. Soils with a high clay content will generally have lower dielectric constant values than coarse soils at the same moisture content since more water is being held in the bound water phase (see Figure 1).

Microwave energy originates from within the soil, with the magnitude of any one soil layer's contribution decreasing with depth. For practical purposes the total thickness of the surface layer which provides most of the measurable energy contribution is defined as the thermal sampling depth [*Schmugge and Choudhury*, 1981]. It is also often referred to as the skin depth or penetration depth.

The energy which is subsequently emitted from the soil surface is affected by the dielectric contrast across the soil-air interface and causes some of the energy to be reflected back downward into the soil. The amount of energy which is reflected back is directly related to the magnitude of this dielectric contrast. The thickness of this layer, which determines the surface emissivity/reflectivity, is often referred to as the soil moisture sampling depth and is thought to be only several tenths of a wavelength thick [*Schmugge*, 1983]. It is the average dielectric property of this layer which determines the emissivity. However, this thickness is somewhat variable and is related to the average moisture content of the layer. As the average moisture content of this layer decreases, its thickness increases. It is the average moisture content of this soil layer which is most strongly related to the emissivity observed above the surface.

3.2. Theoretical Calculations

The theoretical complex soil dielectric constant k_m was calculated for each of the three experimental soils for a range of moisture contents using two common dielectric models, the

Dobson semiempirical model [*Dobson et al.*, 1985] and the Wang-Schmugge model [*Wang and Schmugge*, 1980]. Both models are largely empirical but based on soil physical characteristics. The Dobson semiempirical model does not distinguish between the bound water fraction and the free water fraction in the soil. While the model uses soil textural composition in the optimization of empirical coefficients, it uses the same relationship for the entire range of soil moistures. Although k_m is a complex number, the real and imaginary parts are solved for independently because of the manner in which the equations for the two parts were optimized (M. C. Dobson, personal communication, 1993). Owing to several printing errors in the original publication, the model will be reproduced here. The model states that

$$k'_m = \left[1 + \frac{\rho_b}{\rho_s}(k_s^\alpha - 1) + m_v^{\beta'} k_{fw}'^{\alpha} - m_v\right]^{1/\alpha} \quad (1)$$

$$k''_m = [m_v^{\beta''} k_{fw}''^{\alpha}]^{1/\alpha} \quad (2)$$

where ρ_b and ρ_s are the soil bulk density and particle density (kg/m^3), m_v is the volumetric moisture content, k_s and k_{fw} are the dielectric constants of the soil solids and water, α is an empirical shape factor equal to 0.65, and β is an empirical texture-dependent factor [*Dobson et al.*, 1985]. The real and imaginary parts of the relative permittivity of water were calculated for a given temperature and frequency, f, using a Debye equation as modified by *Dobson et al.* [1985] to account for the effective ionic conductivity of the soil σ_{eff} and are given by

$$k'_{fw} = k_{w\infty} + \frac{k_{w0} - k_{w\infty}}{1 + (2\pi f \tau_w)^2} \quad (3)$$

$$k''_{fw} = \frac{2\pi f \tau_w (k_{w0} - k_{w\infty})}{1 + (2\pi f \tau_w)^2} + \frac{\sigma_{\text{eff}}}{2\pi k_0 f}\frac{\rho_s - \rho_b}{\rho_s m_v} \quad (4)$$

where $k_{w\infty}$ is the high-frequency limit of k_w, k_{w0} is the frequency and temperature-dependent static dielectric constant of water, τ_w is the relaxation time of water equal to $9.2754571 \times 10^{-12}$ s, and k_0 is the permittivity of free space equal to 8.854×10^{-12} F m^{-1}. The empirical, texture-dependent β parameters are given by

$$\beta'_k = 1.2748 - 0.519S - 0.152C \quad (5)$$

$$\beta''_k = 1.33979 - 0.603S - 0.166C \quad (6)$$

where S and C are the sand and clay fractions and σ_{eff} is the effective conductivity, defined as

$$\sigma_{\text{eff}} = -1.645 + 1.939\rho_b - 2.256S + 1.594C \quad (7)$$

An earlier model by *Wang and Schmugge* [1980] for calculating the complex soil dielectric constant was also tested. The basic premise for this model is that the soil dielectric constant is a linear combination of the permittivities of its component parts, i.e., bound water, free water, air, and soil material. Unlike the Dobson model, the Wang-Schmugge model clearly distinguishes between the bound water fraction and the free water fraction by providing separate relationships which describe the two phases. This model also introduces the transition moisture concept. The transition moisture is defined as the moisture content at which the free water phase begins to dominate the soil system and is strongly related to the particle size distribution. The transition moisture content is determined from the wilting point, which may also be derived empirically from the particle size distribution.

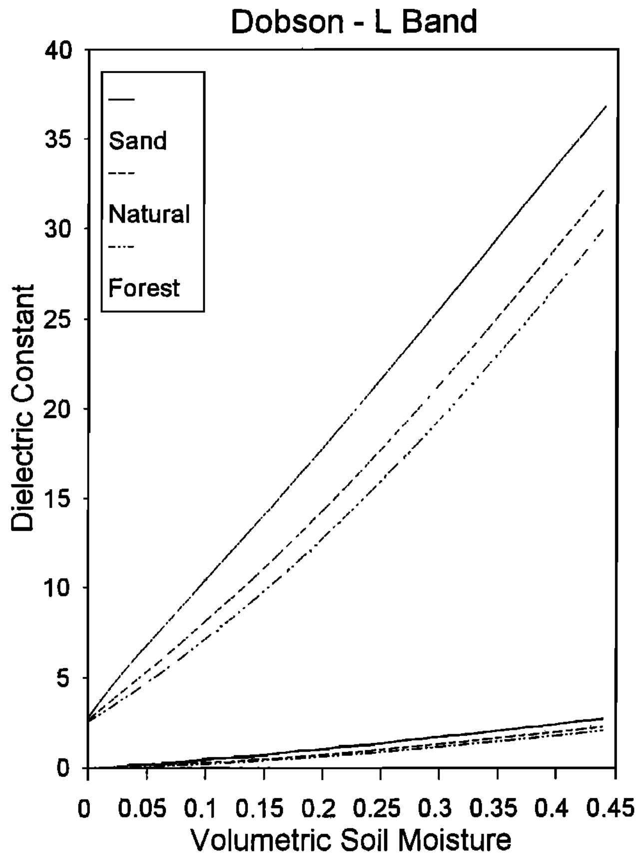

Figure 1. Theoretical soil dielectric as a function of soil moisture for the three experimental soils as calculated by the Dobson semiempirical model at 1.67 GHz.

From the modeled soil dielectric constants (Figures 1 and 2) one sees clearly the effects of soil texture. Since the two wave bands are very comparable, only L band is illustrated. For a given soil moisture a high sand content is seen to exhibit a higher dielectric constant due to the availability of more free water in the soil. Conversely, a higher clay content results in the bound water dominating the soil system over a much wider range in soil moisture. Dielectric constants calculated by the Dobson model (Figure 1) are seen to exhibit greater differences between the three soils than those calculated by the Wang-Schmugge (W-S) model (Figure 2), but they are also more linear and demonstrate little change in the relationship as the moisture content goes from the bound water phase to the free water dominated phase. The main difference between the two models is in the separate treatment of the bound and free water phases of the W-S model.

The difference in the dielectric constant between C and L bands is not large because the dielectric constant of water changes very little in that frequency range. In the field, however, the emissivity differences observed between the two frequencies are often significantly greater. This is due to the effective "penetration depth" (or more accurately, the emitting depth). The penetration depth is defined as the depth at which a signal has only $1/e$ of its original strength remaining. This depth is largely a function of wavelength but is influenced also by soil moisture. Therefore field measurements of soil moisture are seldom sampled in a manner which is the most representative of the true emitting layer for a given wavelength and the existing soil physical conditions.

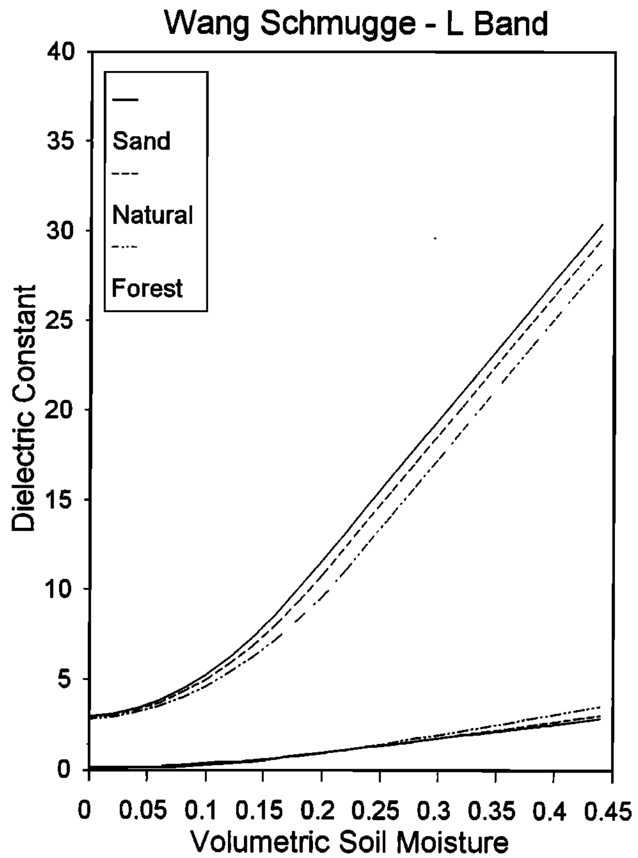

Figure 2. Theoretical soil dielectric as a function of soil moisture for the three experimental soils as calculated by the Wang-Schmugge model at 1.67 GHz.

4. Measurement Results and Discussion

4.1. Laboratory Dielectric Measurements and Model Intercomparisons

Dielectric analyses of the experimental soils were conducted by the Radiation Laboratory of the University of Michigan (laboratory 1) and the Microwave Remote Sensing Group, Firenza, Italy (laboratory 2). The measurements performed by laboratory 1 were made using an HP8753 network analyzer. Calibration was performed relative to distilled water and butanol (M. C. Dobson, personal communication, 1993). Measurements from laboratory 2 were made with a reflectometer probe which measures the real part of the dielectric in a range from approximately 2 to 45 (see *Jackson* [1990] for a thorough description of the procedure). The errors associated with this system are about 3% for the real part and about 8% for the imaginary part. Although this analysis was conducted only at 1.4 GHz, it is still useful for comparative purposes because the difference in the dielectric constant between 1.4 and 1.67 GHz is not great. Errors in the laboratory measurements often occur because of difficulties in achieving the actual field bulk density in a laboratory sample. In addition, it is often difficult to ensure a thorough and uniform mixture of the soil and water because of the relatively small sample size which is used for the dielectric measurement. Water will often separate from the soil and pool at the soil surface or at the interface with the sample holder due to adhesive forces. However, the results of the L band measurements from the two laboratories appear to be reasonably consistent and should attest to their reliability. These measurements compared reasonably well with the modeled dielectrics, except for the sandy soil, and are shown separately for each soil and wave band (Figures 3a–3f). The Dobson model is seen to be consistently higher than the W-S model and is also more linear for all the cases noted in this study. The two models compare best for the forest and natural soils. They are seen to differ more as the sand content of the soil increases. As is the case with most empirical models, both models provide the best results under average conditions or, in this case, for soils with average particle size distributions. Neither model compared well with the laboratory measurements of the sand. It should be pointed out that the sand was not a typical naturally occurring soil but rather one composed of fine to very fine mechanically crushed quartz. Although the moisture retention properties were rather typical for this type of soil, there may be other properties which resulted in the observed differences between the measured and modeled values.

4.2. Field Measurements and Comparison With Calculated Emissivities

Microwave brightness temperature was measured over each of the three soils at both 1.67 GHz and 5 GHz several times during the day throughout the dry-down period. Normalized T_B was calculated by dividing T_B by the average temperature of the emitting layer, according to

$$\varepsilon_s = \frac{T_B}{T_s} \tag{8}$$

where ε_s is the normalized T_B, or estimated surface emissivity. The average emitting layer was estimated to be 1 cm at 5 GHz and 5 cm at 1.67 GHz. Average soil moisture was also calculated for these surface layers and was used to plot against the field data. The moisture profiles for all three plots were found to be relatively uniform to approximately 20 cm at the beginning of the experiment. Moderate moisture gradients formed during the middle period of the experiment, with the steepest gradients during midday. Considerable moisture recovery was frequently made at the surface during the nighttime. During days of high evapotranspiration demand a dry crusty surface layer of several millimeters in thickness would often form. During the latter portion of the experiment, both the sand and the natural soil again approached a more uniform moisture gradient, while the forest soil maintained a somewhat steeper gradient down to about 10 cm.

The Fresnel emissivity [see *Schmugge*, 1985] was calculated from the theoretical dielectric values from both models and compared with the field measurements (Figures 4a–4f). They are seen to agree reasonably well. Although the Fresnel emissivity assumes a uniform moisture gradient within the soil, the calculations are well within the error of the field measurements. The calculated emissivities for the laboratory dielectric measurements also corresponded well with both the field measurements and the theoretical calculations. The field and laboratory measurements appeared to agree best with the W-S model. The best agreement was observed for the forest and natural soils. For the sand, however, it was noticed that the laboratory data began to deviate somewhat from both the model data and the field data as soil moisture exceeded the approximate field capacity of the soil. This was noticed for both wavelengths, although it is not entirely clear why this occurred. It is known, however, that the relatively small size of the laboratory samples occasionally results in measurement errors

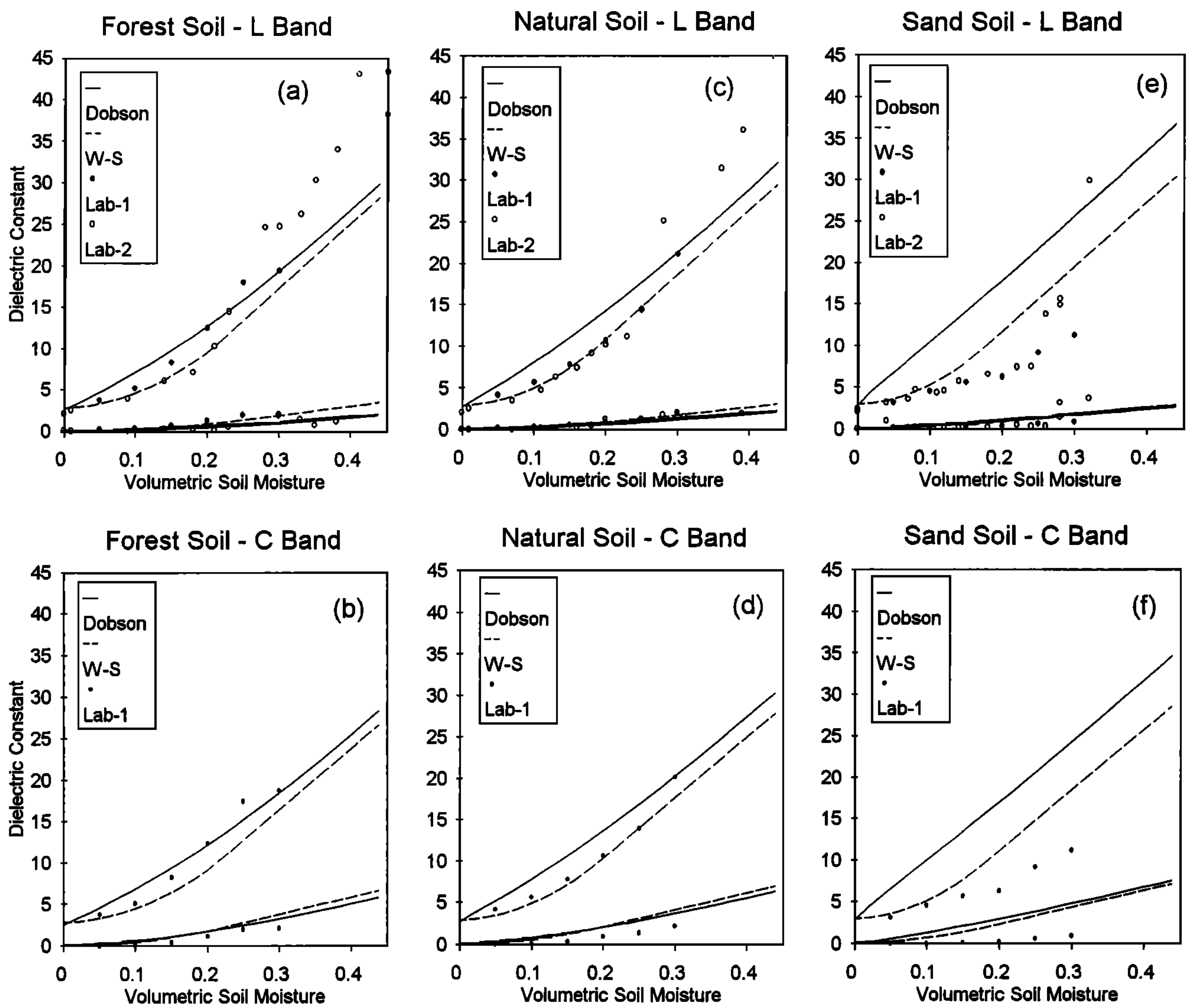

Figure 3. A comparison of the two dielectric models and the laboratory-measured dielectric constants as functions of soil moisture for the forest, natural, and sandy soils at frequencies of (a)–(c) 1.67 GHz and (d)–(f) 5-GHz. Microwave Remote Sensing Group measurements were conducted only at 1.4 GHz.

due to improper mixing and other conditions as discussed previously. The observed trends were relatively consistent for both wave bands.

4.3. Relating Emissivity to Average Moisture Content for Different Surface Layer Depths

Microwave emissivity measured above the soil surface is the result of upwelling radiation integrated over a surface soil layer of certain thickness. The thickness of this layer is directly related to the wavelength of the radiation being measured and inversely related to the soil moisture. Consequently, longer-wavelength radiation is more representative of a deeper soil layer, therefore enabling one to extract more useful information. Radiative transfer theory has shown that while this thickness may actually exceed 1 m for low-frequency radiation, the magnitude of the contribution becomes negligibly small after a comparatively shallow depth, often called the penetration depth. *Mo et al.* [1980] have indicated that this depth is approximately 0.06λ–0.1λ, while *Schmugge* [1985] states that this depth rarely exceeds several tenths of a wavelength. *Ulaby et al.* [1986] have indicated that the penetration depth may range from about a wavelength for a soil with a volumetric moisture content around 4% to about 0.1λ for very wet soils. The maximum emitting depth of the soil may also be a function of soil texture, through its influence on the partitioning of the bound and free water fractions. Studies which have reported radiometer measurements in the L band region have typically used sampling depths from 2 cm to about 5 cm, while measurements at higher frequencies such as C band are generally related to average soil moisture in surface layers of 0.5 cm to a maximum of about 2.5 cm [*Newton and Rouse*, 1980; *Burke and Schmugge*, 1982; *Wang and Choudhury*, 1981; *Wang et al.*, 1983; *Schmugge*, 1985]. *Pampaloni et al.* [1990] found that L band radiometer data taken by aircraft exhibited the highest correlations with the average soil moisture in the top 20-cm surface layer. Owing to a fairly uniform moisture profile down to this depth and a high autocorrelation between the various surface layers, conclusive statements regarding the true penetration depth were difficult to make.

Normalized brightness temperatures at both frequencies were compared with the average soil moisture measured for

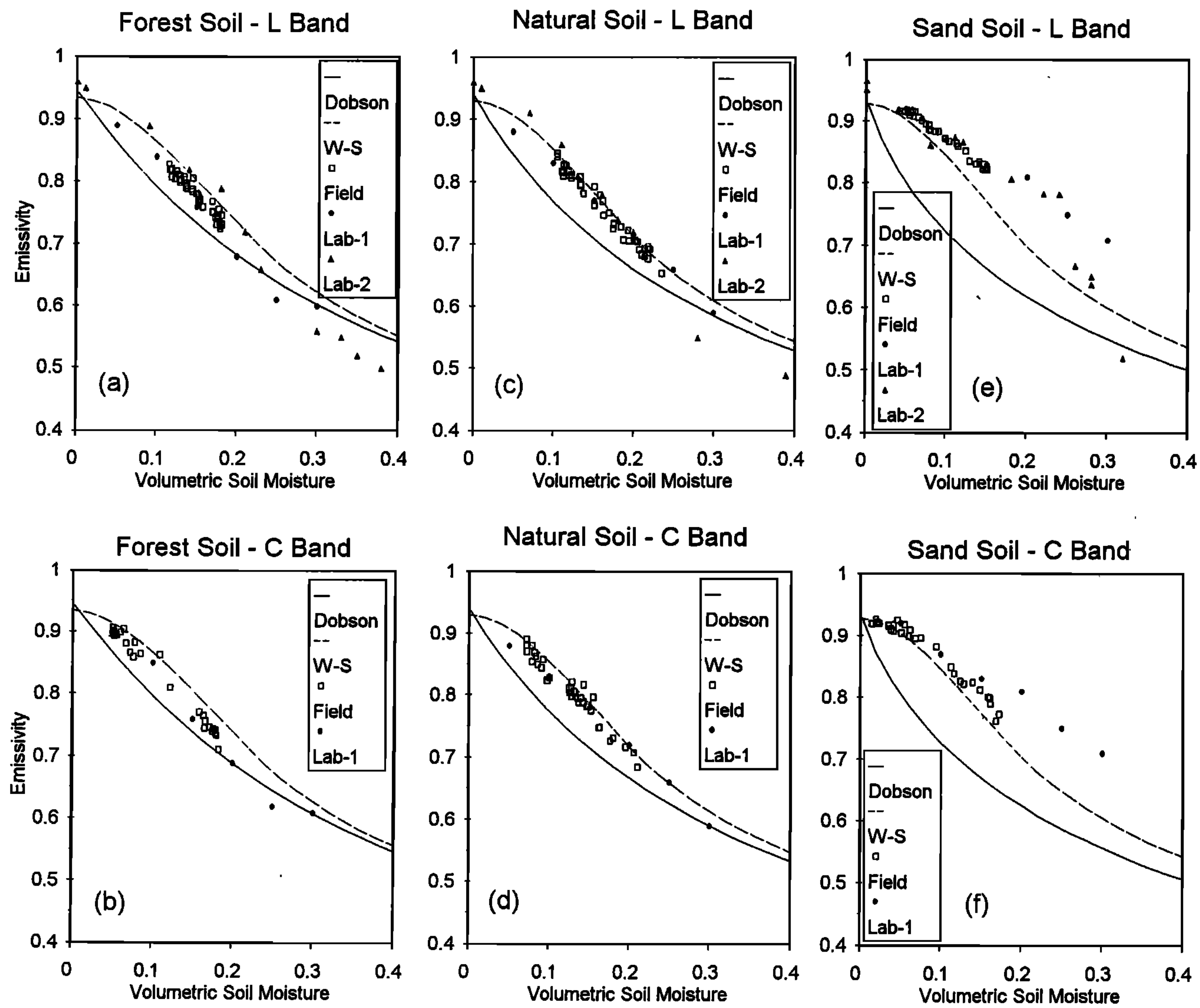

Figure 4. Field-measured emissivities and calculated emissivities as functions of soil moisture for the forest, natural, and sandy soils at frequencies of (a)–(c) 1.67 GHz and (d)–(f) 5 GHz.

surface layers of different depths (Figures 5a–5f). These measurements were made for the 0–0.5, 0–1, 0–2, 0–3, 0–4, 0–5, and 0–8 cm top soil layers. The relationship which is observed to be the most linear and coinciding best with the laboratory-based values might be considered the most representative of the effective penetration depth for a given soil and frequency. The theoretical emissivities are also indicated for each case, but their accuracy is limited by the reliability of the respective dielectric models.

A linear relationship between emissivity and soil moisture will generally exist if the sampling depth is representative of the actual penetration depth of the microwave signal. Under drying conditions, curves which tend to approach the horizontal generally indicate a soil moisture sampling depth which is too deep. In this example the sampled soil layer continues to dry with no noticeable increase in the emissivity. Conversely, a drying curve which approaches the vertical indicates a soil sampling depth which is too shallow. Here the observed emissivity continues to increase, while the observed soil moisture does not change. Penetration depth will vary, however, and will increase as the surface moisture decreases.

4.3.1. Forest soil measurements. At the 5-GHz frequency (Figure 5a), observed emissivity appears to correspond best to soil moisture in the top 1-cm layer. It also agreed best with the laboratory-based calculations. Soil moisture sampled in the 0–2 cm layer appears to be somewhat deep. At L band (Figure 5b) the 0–5 cm average soil moisture appears to be related well to the radiometer measurements. However, the 0–8 cm data also fall within limits of the laboratory values. The actual penetration depth may be somewhere between these two depths.

4.3.2. Natural soil. Only 0–1 cm and 0–5 cm soil moisture measurements were taken in the natural soil. The 0–1 cm average soil moisture agrees best with the 5-GHz emissivity (Figure 5c), although the 0–5 cm average soil moisture values are also quite linear. For the 1.67-GHz data (Figure 5d) the 0–5 cm average moisture falls between the calculated emissivities of the laboratory measurements. It also agrees well with the W-S model.

4.3.3. Sandy soil. The 5-GHz data (Figure 5e) display good relationships for both 0–1 cm and 0–2 cm average soil moisture. At the longer wave band the 0–5 cm average mois-

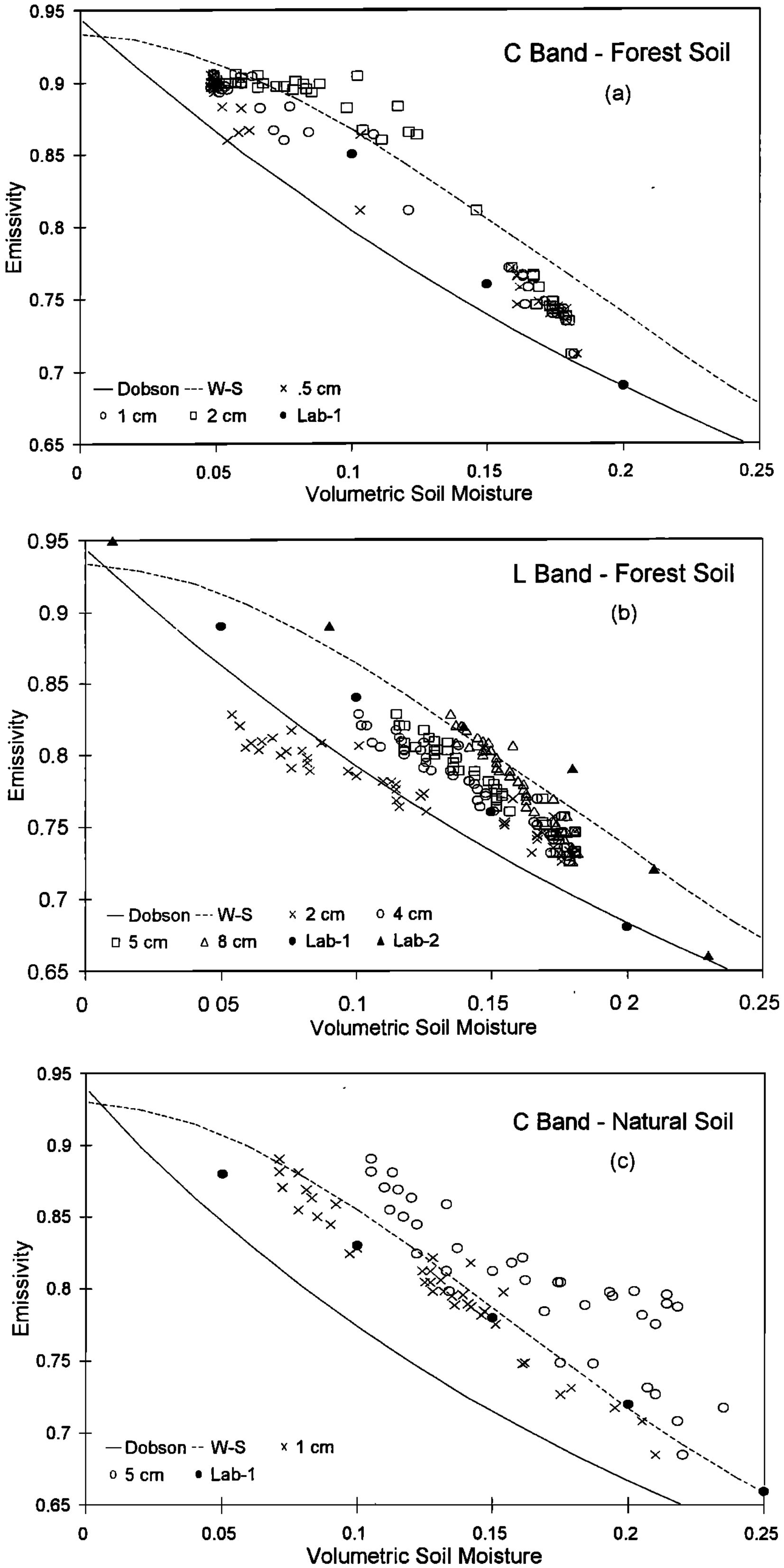

Figure 5. Field-measured emissivities as a function of the average moisture content for several different top soil layers at 5 GHz and 1.67 GHz for the (a)–(b) forest, (c)–(d) natural, and (e)–(f) sand soils.

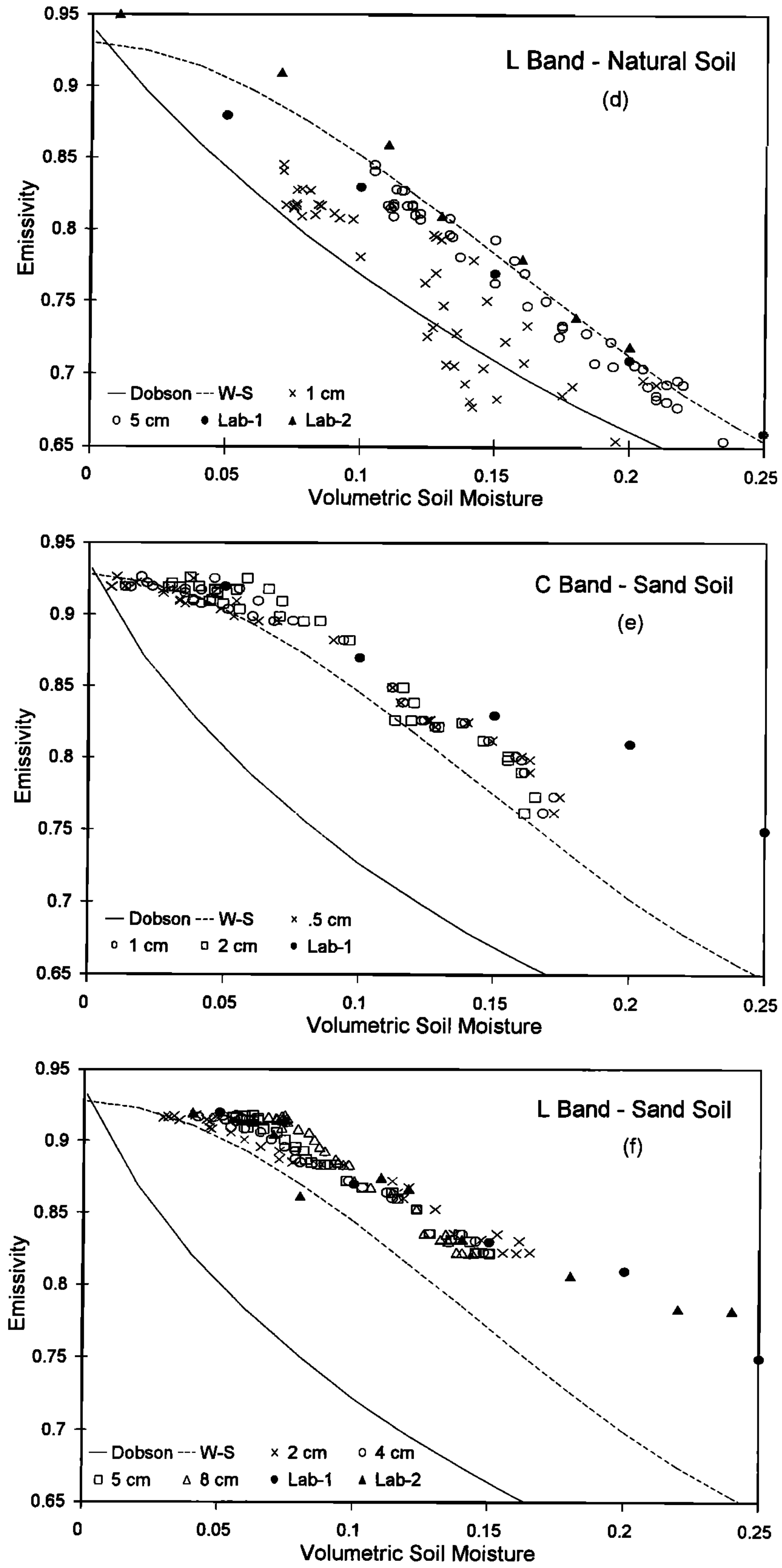

Figure 5. (continued)

ture data appear to exhibit the best relationship with observed emissivity (Figure 5f). Although the 0–8 cm average soil moisture also appears linear, it does not compare well with the laboratory measurements.

5. Summary and Conclusions

Circularly polarized microwave brightness temperature measurements were made at frequencies of 5 GHz and 1.67

GHz over three soils with different textural characteristics. After normalizing the brightness temperature with the physical soil temperature, the microwave data were compared with the average soil moisture of surface layers of different thicknesses. Laboratory dielectric measurements were also made for the three soils. Dielectric curves based on the soil physical characteristics were calculated by two different models for each of the soils and compared. The Dobson semiempirical model was found to be more linear and generally higher than the Wang-Schmugge model. The differences between the two models were found to increase with an increase in sand content and a decrease in clay content. The separate treatments for the bound and free water fractions in the soil and the use of the transition moisture concept by the W-S model appear to make it more closely aligned with the laboratory measurements.

Except for the sandy soil, the field measurements were found to be consistent with the calculated Fresnel emissivities based on the laboratory dielectric constant measurements and the two dielectric models, although the Wang-Schmugge model appeared to give somewhat better agreement. The observed emissivities at both measurement frequencies were plotted against the average soil moisture for several surface layers ranging in thickness from 0–0.5 to 0–8 cm. Definite conclusions could not be made about the dependence of the penetration depth on soil moisture and/or soil texture. Even though sand content for the three soils ranged approximately from 57% to 93%, the overall range in clay content appears to be insufficient to demonstrate any meaningful dependence on soil texture. This observation may have useful implications for satellite inverse modeling of soil moisture, however, in that modeling adjustments which account for differences in soil texture may not be that critical for most soils, unless they possess significant amounts of clay. Although the precise penetration depth could not be confirmed, it appeared that the 5-GHz data could be characterized best by the average soil moisture in a surface layer somewhere between 1 and 2 cm in thickness. At the 18-cm wavelength the emissivity seems to relate well to the average soil moisture at both 0–5 and 0–8 cm. The results appear to indicate that (at least for 1.67 GHz) microwave radiometers may be able to see somewhat beyond the theoretically defined effective penetration depth, which is often given at about several tenths of a wavelength. Since often there exists a strong autocorrelation between surface layers of different thickness, one may also be able to make reasonable remotely sensed soil moisture estimates for layers well below the effective sampling depth. The results appear to provide support for continued satellite-based soil moisture research even at C band, the potential of which has already been demonstrated [*Van de Griend and Owe*, 1994], at least in those regions of limited or discontinuous vegetation cover.

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